Software Design Requirements

For the

Shuttle Remote Manipulator System

A NASA CI03
SARP Initiative 583
IVV-70 Project

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1 Introduction

This specification has been developed to support a research project funded by the NASA Software Assurance Research Program (SARP) during the fiscal year 2003. A system-level, executable specification (ES) based simulation of the Shuttle Remote Manipulator System (SRMS) has been created from the requirements specified in the System Requirements (SARP-I583-001) and Simulator Requirements (SARP-I583-002) Specifications, and will be used as a vehicle for exploring the concepts described in section 2 of Triakis proposal number TC_G020614.

This document establishes the design requirements for the RMS Computer software that will implement the SRMS functionality as specified in the System Requirements Specification (SARP-I583-001) and the System Design Document (SARP-I583-101). We are creating a simulator for the primary purpose of determining the feasibility of using the same tests created to verify an ES-based system design, to verify the software developed to implement the specified behavior. Further, new methods of gathering software metrics through use of the simulator will be sought, explored, and evaluated.

The format and content of this specification is designed to follow the System Requirements Specification (SARP-I583-001) and the System Design Document (SARP-I583-101) from which this specification has been developed. As our project effort progresses, this specification will be updated to reflect changes to the scope and fidelity of system requirements due to an improved understanding of the extent that our virtual SRMS must be developed to support our research goals.

1.1 System purpose

The system specified herein is intended to represent the SRMS in a general sense only. The virtual system simulator developed for this project will be used as a vehicle to facilitate the research goals stated in Triakis proposal number TC_G020614. As such, system components and functions of the real-world SRMS that are not required to support our research goals have been omitted.

While the purpose of the actual SRMS is to facilitate the deployment and retrieval of shuttle payloads as well as extra-vehicular activity missions, the derivative SRMS will not incorporate functioning end-effectors required for these purposes. The specified SRMS will demonstrate limited control and movement capability of the RMA along with simulated cameras and video monitors showing the RMA position.

1.2 System scope

The SRMS approximately models a subset of the system characteristics of the existing NASA space shuttle RMS. Adaptations to the functionality of the actual SRMS have been incorporated to the extent required for the stated research purposes and demonstration of the research results.

1.3 Definitions, acronyms, and abbreviations

AFDX Avionics Full Duplex Switched Ethernet
CCTV Closed-Circuit Television
CI03 Center Initiative for fiscal year 2003
C/W Caution/Warning
DE Detailed Executable
ES Executable Specification
EVA Extra Vehicular Activity
IV&V Independent Verification and Validation

N/A	Not Applicable
NASA	National Aeronautics & Space Administration
OSMA	Office of Safety and Mission Assurance
PDRS	Payload Deployment and Retrieval System
RHC	Rotational Hand Controller
RMA	Remote Manipulator Arm
RMS	Remote Manipulator System
RMSC	RMS Computer
RMSCP	RMS Control Panel
SARP	Software Assurance Research Program
SimRS	Simulator Requirements Specification
SRMS	Shuttle Remote Manipulator System
SyDD	System Design Document
SyRS	System Requirements Specification
THC	Translational Hand Controller
VSIL	Virtual System Integration Laboratory

1.4 References

http://spaceflight.nasa.gov/shuttle/reference/index.html NASA Shuttle Reference web site

http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/sts-deploy NASA PDRS web page

ISBN 0-345-34181-3 Joels, Kennedy & Larkin; Ballantine books, 1988:
The Space Shuttle Operator's Manual (Revised Edition)

SARP-I583-001 System Requirements Specification for the Shuttle Remote Manipulator System

SARP-I583-101 System Design Document for the Shuttle Remote Manipulator System

SARP-I583-205 System Test Design Document for the Shuttle Remote Manipulator System

TC_G020614 Triakis proposal to NASA for the SARP (Solicitation No: NRA SARP 0201), 14 June 2002

1.5 SRMS overview

Please refer to the NASA PDRS web page for a more complete description of the real space shuttle SRMS that this system is designed to resemble. The following excerpt is included for quick reference:

> *The payload deployment and retrieval system (PDRS) includes the electromechanical arm that maneuvers a payload from the payload bay of the space shuttle orbiter to its deployment position and then releases it. It can also grapple a free-flying payload, maneuver it to the payload bay of the orbiter and berth it in the orbiter. This arm is referred to as the remote manipulator system (RMS).*
>
> *The shuttle RMS is installed in the payload bay of the orbiter for those missions requiring it. Some payloads carried aboard the orbiter for deployment do not require the RMS.*
> *The RMS is capable of deploying or retrieving payloads weighing up to 65,000 pounds. The RMS can also be used to retrieve, repair and deploy satellites; to provide a mobile extension ladder for extravehicular activity crew members for work stations or foot restraints; and to be used as an inspection aid to allow the flight crew members to view the orbiter's or payload's surfaces through a television camera on the RMS.*

2 General system description

2.1 System design description

Power is supplied to the SRMS from the 115vac main shuttle avionics power bus via a circuit breaker on the Power Control Panel. The RMS Computer converts the incoming power to DC voltages suitable to power its own electronics as well as those within the RMS Control Panel. The Power Contol Panel supplies power to the shuttle bay cameras and the Remote Manipulator Arm as well. Figure 1 contains a block diagram of the Shuttle Remote Manipulator System.

The RMS Computer communicates with the Remote Manipulator Arm and the cameras in the shuttle bay via Avionics Full Duplex Switched Ethernet (AFDX) serial high-speed databuses. In addition to commands and status information, digital compressed video from the CCTV cameras are conveyed over these databuses.

The RMS Computer converts the compressed digital camera video signals into RGB format to drive the video inputs of the two video display monitors located on the RMS Control Panel. The RMS Computer communicates with the RMS Control Panel via the Serial Peripheral Interface bus.

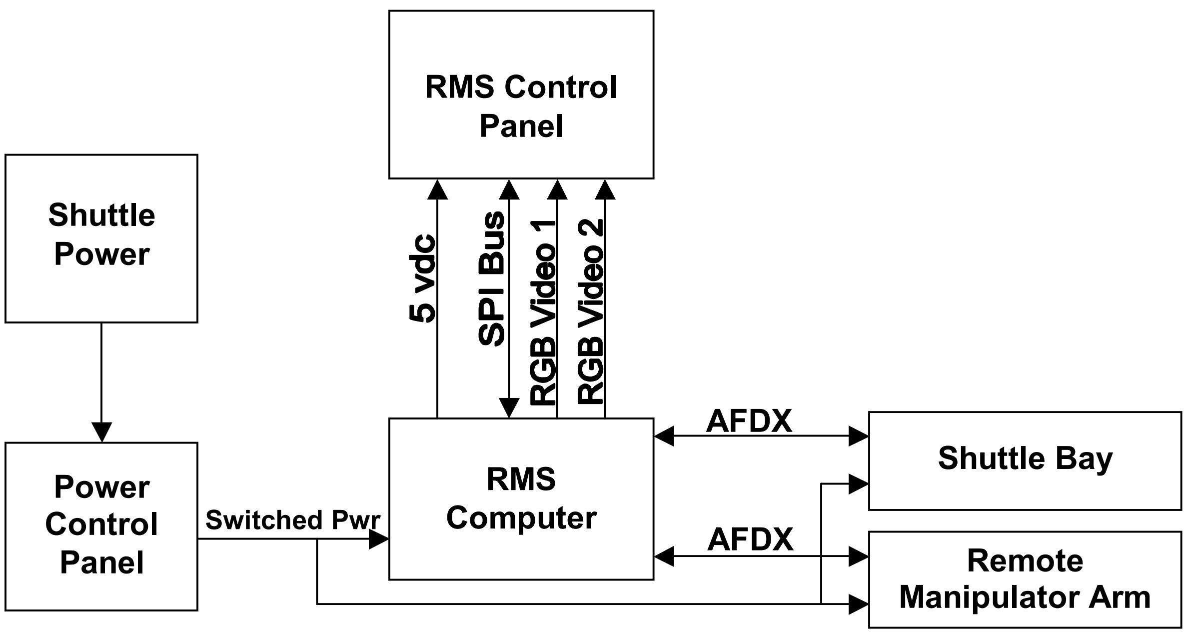

Figure 1: Shuttle RMS Block Diagram

2.2 RMA description

The RMA is implemented with 6 degrees of freedom corresponding roughly to the joints of the human arm i.e.: shoulder yaw & pitch joints; elbow pitch joint; and wrist pitch, yaw, & roll joints.

The SRMS design incorporates five CCTV video cameras rather than the four specified in the System Requirements Specification. The extra camera has been added to the RMA near the shoulder joint for added visual awareness. The remaining four cameras are positioned as stated in the SyRS i.e.:

- One at the RMA wrist joint,
- One at the RMA elbow joint,

- One at the aft wall of the shuttle bay, and
- One at the fore wall of the shuttle bay.

All cameras may be positioned via motor-driven pan, tilt, & zoom functions. The operator controls the position and zoom degree of each motor independently through buttons on the camera control panel.

The RMS Control Panel incorporates two video display monitors for displaying CCTV video from any of the five video cameras. Split screen capability was not implemented due to budget constraints since this feature is not required to meet the objectives of this project.

3 Software performance requirements

3.1 RMS Control Panel

The RMS control & display panel, located in the real-world shuttle at the aft crew station, is the primary interface through which the operator controls the RMA. Selection of the various operational modes and states is achieved through the RMS control & display panel. The SRMS does not implement all of the functions and modes incorporated in its real-world counterpart, but only the subset described in the System Design Document (SARP-I583-101).

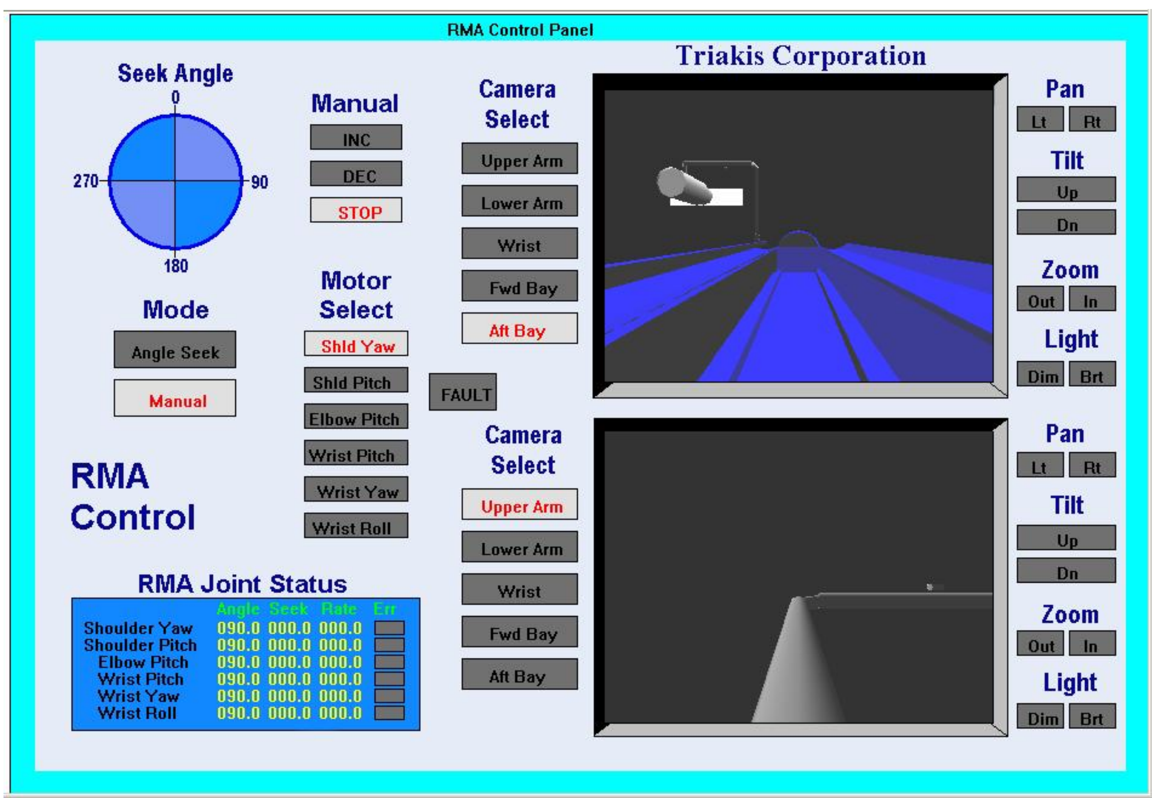

Figure 2: Simulator RMS Control & Display Panel (preliminary)

The RMS Control Panel will be implemented only as an ES part for this project. As such, there will be no software written to run on the target microprocessor-based design that would otherwise be developed from the ES. Since the software that will be written to drive the RMS Computer must interface with the control panel, information on the data passing between them is included here.

The RMS Control Panel, shown in Figure 2, comprises an array of backlit pushbutton switches and indicators with which the RMS operator inputs commands and monitors the operation of the RMA. The control panel monitors the state of all inputs and sends data to the RMS Computer only when it detects activation of a button. The panel also manages pushbutton and status indicator illumination, as well as the display of camera video.

The RMS Control Panel communicates with the RMS Computer via the industry standard SPI bus. All user activated control inputs are passed to the RMS Computer. Displayed data are driven by inputs received from the RMS Computer via the SPI bus. The RMS Computer and the RMS Control Panel may each send data asynchronously to the other. Table 1 lists the message formats used for sending data from the RMS Control Panel to the RMS Computer

Table 1: RMS Control Panel SPI Bus Output Data Message Formats

Packet ID Data[0]	Data Word No.	Data Definition
0 = Select Mode	Data[1]	0 = Angle Seek command mode 1 = Manual command mode
1 = Select Motor	Data[1]	0 = shoulder yaw motor 1 = shoulder pitch motor 2 = elbow motor 3 = wrist pitch motor 4 = wrist yaw motor 5 = wrist roll motor
2 = Manual Command	Data[1]	0 = Increment 1 = Decrement 2 = Stop 3 = Command Buttons Off
3 = Angle Seek	Data[1]	0 = Shoulder Yaw 1 = Shoulder Pitch 2 = Elbow Pitch 3 = Wrist Pitch 4 = Wrist Yaw 5 = Wrist Roll
	Data[2]	Seek Angle Integer
	Data[3]	Seek Angle Fraction * 4096
4 = Video1 Select	Data[1]	0 = Upper Arm camera 1 = Lower Arm camera 2 = Wrist camera 3 = Forward Bay camera 4 = Aft Bay camera
5 = Video2 Select	Data[1]	0 = Upper Arm camera 1 = Lower Arm camera 2 = Wrist camera 3 = Forward Bay camera 4 = Aft Bay camera
6 = Camera 1 Control	Data[1]	**Camera 1 Control Word (packed bits)**

Packet ID Data[0]	Data Word No.	Data Definition
		1 = Pan Left 2 = Pan Right 4 = Tilt Up 8 = Tilt Down 10 = Zoom In 20 = Zoom Out 40 = Light Dim 80 = Light Bright
7 = Camera 2 Control	Data[1]	**Camera 2 Control Word (packed bits)** 1 = Pan Left 2 = Pan Right 4 = Tilt Up 8 = Tilt Down 10 = Zoom In 20 = Zoom Out 40 = Light Dim 80 = Light Bright

3.2 RMS Computer

The RMS Computer contains the central processor that is programmed to control the entire system in response to commands entered via the RMS Control Panel. A block diagram of the RMS Computer is shown in Figure 3.

The Computer design is based upon the Motorola MPC555, a PowerPC core microcontroller chip. With its high level of integrated functions, the MPC555-based design requires peripheral circuitry only for the AFDX interfaces and to manage the conversion of digital video to RGB video. In addition to the MPC555, the RMS Computer comprises a power converter, an AFDX router, and a digital to RGB converter.

The power converter is responsible for converting the incoming shuttle electrical power into DC power required internally and by RMS Control Panel subsystem. The AFDX router directs communication between the MPC555 and all subsystem elements connected to the AFDX data buses. The Digital to RGB converter receives compressed digital camera video data from the source selected at the control panel and outputs video data in standard RGB format for display on the corresponding control panel video monitor.

The RMS Computer software is responsible for controlling the RMA and video cameras in response to commands entered by the operator through the RMS Control Panel. This is accomplished by:

a) Receiving operator input from the control panel SPI bus in the form shown in Table 1;
b) Communicating with the RMA subsystems and shuttle bay cameras via the AFDX interface; and
c) Sending the correct RGB camera video, and RMA status to the RMS Control Panel.

All RMA subsystems communicate solely with the RMS Computer over the AFDX data bus. The RMS Computer AFDX address is 0x0000.

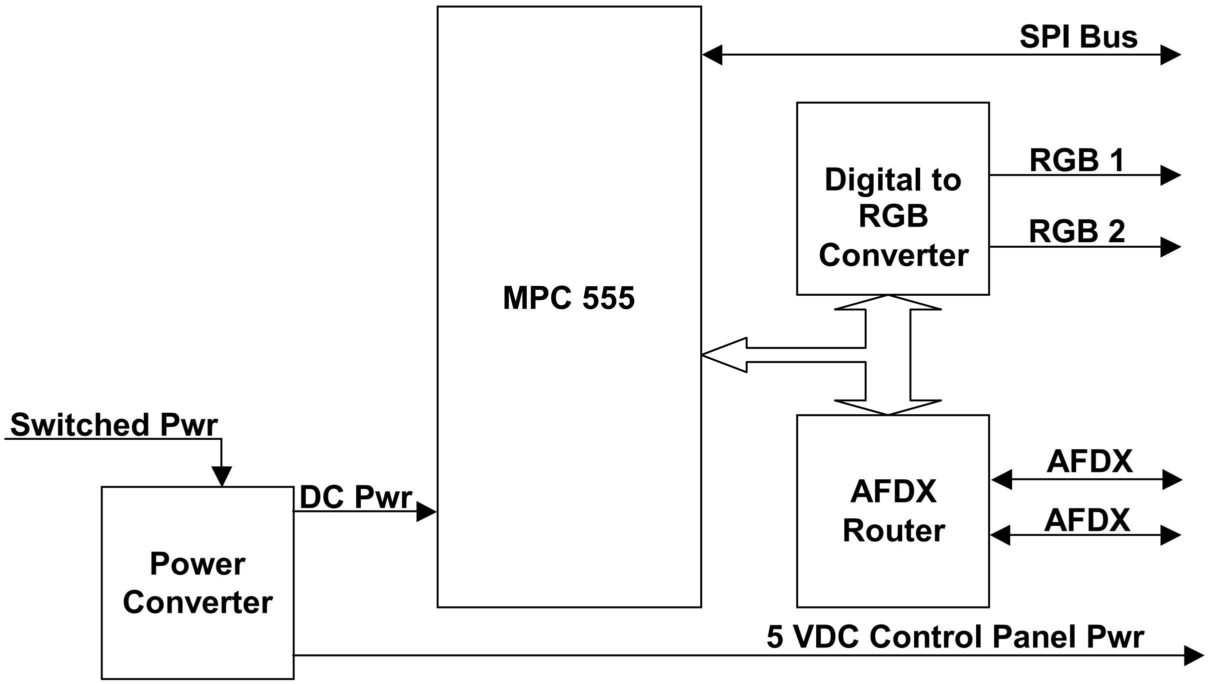

Figure 3: RMS Computer Block Diagram

When the arm is in the "Stowed" position, all joint angles are at zero degrees except for the shoulder yaw joint which is at 180º. Positive angle movements correspond to: Pitch up, Yaw right, Roll right as viewed looking down the arm from the shoulder. The RMA parts are physically connected in the following sequence:

a. Shoulder Yaw joint
b. Shoulder Pitch joint
c. Upper arm boom
d. Elbow joint
e. Lower arm boom
f. Wrist Pitch joint
g. Wrist Yaw joint
h. Wrist Roll joint
i. End Effector

Additionally, the Upper arm, Lower arm, and Wrist all have cameras mounted on them.

The SRMS allows the operator to move the arm on a joint-by-joint basis with full computer support in either fully "Manual" or "Angle Seek" modes. The RMA joint to be controlled is selected through six pushbuttons on the RMS Control Panel corresponding to: Shoulder Yaw, Shoulder Pitch, Elbow, Wrist Yaw, Wrist Pitch, and Wrist Roll.

Manual mode is controlled through three push buttons on the RMS Control Panel: Increment, Decrement, and Stop. When the "INC" button is pressed, the selected joint angle increments at a rate of 7.2 degrees/sec. Conversely, when the "DEC" button is pressed, the selected joint angle decrements at a rate of 7.2 degrees/sec. The selected joint will continue moving at a constant rate until the "STOP" button is pressed.

Angle Seek mode allows the operator to select a destination angle to which the joint is to be positioned. The operator inputs the desired destination angle by clicking on the corresponding spot on a 360-degree circle graphic located in the upper left corner of the RMS Control Panel. The present joint angle is indicated with a marker on the circle and a destination marker appears where the mouse is clicked. The computer automatically increments or decrements the selected joint angle at a rate of 7.2 degrees/sec to arrive at the destination angle in the shortest time possible.

3.2.1 RMS Computer initialization

The RMS Computer shall initialize all elements of the SRMS under its control to a safe “at-rest” state upon power-up. The RMS Control Panel shall initialize the RMA in “Manual Command” control mode with all RMA joints stopped. The Aft shuttle bay and upper arm camera views shall be displayed on the video monitors.

3.2.2 RMA control & communications

The AFDX address map for devices located in the RMA assembly is given in Table 2.

Table 2: RMA Device AFDX Bus Address Map

Address	Receiver
0x200	Shoulder Pitch Controller
0x210	Shoulder Yaw Controller
0x300	Elbow Pitch Controller
0x400	Wrist Pitch Controller
0x410	Wrist Yaw Controller
0x420	Wrist Roll Controller
0x431	Camera Pitch Controller
0x432	Camera Yaw Controller
0x433	Camera Zoom Controller
0x434	Camera Lamp
0x435	Camera Image Sensor
0x770	Lower Arm Camera Controller
0x771	Camera Pitch Controller
0x772	Camera Yaw Controller
0x773	Camera Zoom Controller
0x774	Camera Lamp
0x775	Camera Image Sensor
0x776	Lower Arm Data Module (for strain gauge data)
0x780	Upper Arm Camera Controller
0x781	Camera Pitch Controller
0x782	Camera Yaw Controller
0x783	Camera Zoom Controller
0x784	Camera Lamp
0x785	Camera Image Sensor
0x786	Upper Arm Data Module (for strain gauge data)

There are three basic message types used by the RMS Computer to communicate with all AFDX devices:

a) **Query Status – All:** Requests the status of all AFDX devices;
b) **Query Response:** Requests data of a specific AFDX device;
c) **Execute Command:** Issues a command for a specific AFDX device to execute.

AFDX messages from the RMS Computer to the Motor Controllers take the form shown in Table 3.

Table 3: AFDX Data Packet from RMS Computer to Motor Controllers

Message Type	AFDX Dest. Addx	Src Addx Data[0]	Data Type Data[1]	Data Wd Data[2]
1 = Query Status - All	Unused	0x0000	Unused	Unused
2 = Query Response	Device Addx	0x0000	1 = Status 4 = Motor Velocity 5 = Motor Angle 6 = Joint Angle (degrees)	Unused
3 = Execute Command	Device Addx	0x0000	2 = Self Test	Unused
			4 = Motor Velocity (RPM)	16-bit Integer

The motor controllers respond to commands from the RMS Computer with a status update and/or command acknowledgement message in the format shown in Table 4.

Table 4: AFDX Data Packet from Motor Controller

Message Type	AFDX Dest. Addx	Src. Addx Data[0]	Data Type Data[1]	Status Wd Data[2]	Data Wd Data[3]	Data Wd Data[4]
1 = Query Status - All	0x0000	Device Addx	1 = Status	16-bit status word	Unused	Unused
2 = Query Response	0x0000	Device Addx	1 = Status	16-bit status word	Unused	Unused
			4 = Motor Velocity	16-bit status word	16-bit Integer	Unused
			5 = Motor Angle	16-bit status word	0x0000	Unused
			6 = Joint Angle (degrees)	16-bit status word	Joint Angle Integer	Joint Angle Fraction * 4096
3 = Execute Command	0x0000	Device Addx	1 = Status	16-bit status word	Unused	Unused

The Data Module is a four-channel analog data acquisition unit used to read the strain gauges and provide the interface to the AFDX bus. Table 5 and Table 6 list the AFDX command and response data formats used for communicating with the Data Module part. Command and data words are 32 bit integer values and the maximum amount of message data is 16 words.

Table 5: AFDX Messages from RMS Computer to Data Modules

Message Type	AFDX Dest. Addx	Src Addx Data[0]	Data Type Data[1]	Data Wd Data[2]
1 = Query Status - All	Unused	0x0000	Unused	Unused
2 = Query Response	Device Addx	0x0000	1 = Status	Unused
			7 = Resistance	0 = Ch. No. 0 1 = Ch. No. 1 2 = Ch. No. 2 3 = Ch. No. 3
3 = Execute Command	Device Addx	0x0000	2 = Self Test	Unused

The Data Module sends messages only in response to commands from a controlling device (e.g. RMS Computer). The format of the Data Module response messages is shown in Table 6. The Message Type field contains the code for the RMS Computer message for which the response has been generated.

Table 6: AFDX Messages from Data Module to the RMS Computer

Message Type	AFDX Dest. Addx	Src. Addx Data[0]	Data Type Data[1]	Status Wd Data[2]	Data Wd Data[3]	Data Wd Data[4]
1 = Query Status - All	0x0000	Device Addx	1 = Status	16-bit status word	Unused	Unused
2 = Query Response	0x0000	Device Addx	1 = Status	16-bit status word	Unused	Unused
			7 = Resistance	16-bit status word	0 = Ch. No. 0 1 = Ch. No. 1 2 = Ch. No. 2 3 = Ch. No. 3	Resistance (16-bit Integer)
			3 = Cmd Error	16-bit status word	Ch. No.	1 = Invalid Ch. No.
3 = Execute Command	0x0000	Device Addx	1 = Status	16-bit status word	Unused	Unused

3.2.3 RMS Control Panel communications

Table 5 lists the SPI Bus Packet ID and data sent by the RMS Computer to the RMS Control Panel. The data types shown in the Packet ID column identify the type of data being received. RMS Computer data is used to update the RMA joint status display, control the backlight of the manual control switches, and to light or extinguish the 'Fault' lamp. All data packets consist of 16-bit words sent in the sequence given in Table 7.

Table 7: RMS Computer SPI Bus Data Packet Contents

Packet ID Data[0]	Data Word No.	Data Definition
0 = Panel Display Data	Data[1]	**Display Row (RMA Joint)** 0 = Shoulder Yaw 1 = Shoulder Pitch 2 = Elbow Pitch 3 = Wrist Pitch 4 = Wrist Yaw 5 = Wrist Roll
	Data[2]	Joint Angle Integer
	Data[3]	Joint Angle Fraction * 4096
	Data[4]	Seek Angle Integer
	Data[5]	Seek Angle Fraction * 4096
	Data[6]	Joint Rate Integer
	Data[7]	Joint Rate Fraction * 4096
1 = Manual Command Data	Data[1]	**RMA Joint** 0 = Shoulder Yaw 1 = Shoulder Pitch 2 = Elbow Pitch 3 = Wrist Pitch 4 = Wrist Yaw 5 = Wrist Roll
	Data[2]	0 = Increment 1 = Decrement 2 = Stop 3 = Command Buttons Off
2 = Fault Data	Data[1]	**Fault Data Word (packed bits: 1 = Fault)** 0x 1 = Master Fault 0x 2 = Shoulder Yaw Fault 0x 4 = Shoulder Pitch Fault 0x 8 = Elbow Pitch Fault 0x 10 = Wrist Pitch Fault 0x 20 = Wrist Yaw Fault 0x 40 = Wrist Roll Fault

3.2.4 Video camera communications

All communications between the RMS Computer and the cameras are accomplished through AFDX serial data buses. An AFDX router located in the shuttle bay provides a connection to the single AFDX bus link from the RMS Computer and the two shuttle bay cameras. The AFDX address map for the bay cameras is given in Table 8. The yaw, pitch, and zoom motors in the shuttle bay cameras are controlled in the same manner as described in section 3.2.1 for the RMA joint and camera motors.

Table 8: Shuttle Bay AFDX Bus Address Map

Address	Receiver
0x141	Forward Bay Camera Pitch Controller
0x142	Forward Bay Camera Yaw Controller
0x143	Forward Bay Camera Zoom Controller
0x144	Forward Bay Camera Lamp
0x145	Forward Bay Camera Image Sensor
0x151	Aft Bay Camera Pitch Controller
0x152	Aft Bay Camera Yaw Controller
0x153	Aft Bay Camera Zoom Controller
0x154	Aft Bay Camera Lamp
0x155	Aft Bay Camera Image Sensor

Each camera has an integrated lamp that can be set to a desired illumination level on command from the RMS Computer. Table 9 gives the AFDX command format for controlling the camera lighting. Lamp intensity is proportional to the data value, with 0 being OFF and 100 being maximum illumination.

Table 9: AFDX Command for Camera Light Control

Message Type	AFDX Dest. Addx	Src Addx Data[0]	Data Type Data[1]	Data Type Data[2]
3 = Execute Command	Device Addx	0x0000	8 = Illumination	Lamp Intensity (0-100%) (Integer)

Each camera has an integrated image sensor that is responsible for transmitting the current camera view upon command from the RMS Computer. There are three basic message types used by the RMS Computer to communicate with all AFDX devices:

a) **Query Status – All:** Requests the status of all AFDX devices;
b) **Query Response:** Requests data of a specific AFDX device;
c) **Execute Command:** Issues a command for a specific AFDX device to execute.

AFDX messages from the RMS Computer to the Image Sensors take the form shown in Table 10. The Execute Command message is intended for future conceived capabilities.

Table 10: AFDX Commands to the Camera Image Sensor

Message Type	AFDX Dest. Addx	Src Addx Data[0]	Data Type Data[1]
1 = Query Status - All	Unused	0x0000	Unused
2 = Query Response	Device Addx	0x0000	1 = Status
			9 = CamImage
3 = Execute Command	Device Addx	0x0000	2 = Self Test

The Image Sensor sends messages only in response to commands from the RMS Computer. The format of the Image Sensor response messages is shown in Table 11. Responses to the three basic message types used by the camera image sensors to communicate with the RMS Computer are:

a) **Query Status – All:** Sends a 16-bit status word (0x0000 = Healthy);
b) **Query Response:** Sends 320x240x4 byte image bitmap;
c) **Execute Command:** No commands currently supported, acknowledges with sensor status.

Table 11: AFDX Responses from the Camera Image Sensor

Message Type	Dest. Addx	Src. Addx Data[0]	Data Type Data[1]	Status Wd Data[2]	Pointer Flag	Num Bytes	Data Pointer
1 = Query Status - All	0x0000	Device Addx	1 = Status	16-bit status word	FALSE	Unused	Unused
2 = Query Response	0x0000	Device Addx	1 = Status	16-bit status word	FALSE	Unused	Unused
			9 = Camera Image	16-bit status word	TRUE	307,200	Pointer to Image Bitmap
3 = Execute Command	0x0000	Device Addx	1 = Status	16-bit status word	FALSE	Unused	Unused

3.3 Testability

The motor controllers are designed to report if the motor subsystem that it controls is not responding according to design. All of the motor controllers and subsystems in the RMA and cameras are identical in this design and support the insertion and detection of faults for testing purposes. Fault reporting is facilitated through the use of subsystem status words.

4 System testing

Refer to the System Test Design Document for information related to system testing.